Evaluation of machining performance of pineapple filler based reinforced polymer composites using abrasive water jet machining process

Jagadish[1], Kapil Gupta[2*], Maran Rajakumaran[3]

[1]Department of Mechanical Engineering, National Institute of Technology Raipur-India

[2*]Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Doornfontein-2028, Johannesburg, Republic of South Africa

[3]Department of Mechanical Engineering, National Institute of Technology Silchar, Assam, India

*Corresponding Author- kgupta@uj.ac.za

Abstract. In the present scenario, polymer composites are being used in various applications such as defence, building construction, aerospace, and packaging etc. due to their unique properties. Machining of polymer composites using conventional machining methods is extremely difficult and expensive. Therefore, non-conventional machining technologies have been explored. This paper presents the results of experimental investigation conducted on abrasive water jet machining of pineapple filler based reinforced polymer composites. A total of nine experiments have been conducted based on Taguchi's robust design of experiment technique considering four input parameters such as stand of distance, working pressure, nozzle speed, and abrasive grain size. Material removal rate and surface roughness parameters are considered as machinability indicators. The optimum machinability indicators obtained are material removal rate- 71 g/s, and average surface roughness- 0.13 µm. The current research identifies abrasive water jet machining process as a sustainable substitute of conventional processes for machining pineapple filler based reinforced polymer composites.

1. Introduction

Composites have become inevitable in present scenario due to their excellent specific characteristics such as high strength, lightweight and better corrosion resistance. Composites especially polymer composites are made of matrix (epoxy resin) and reinforcement (fibers) materials. Among the various polymer composites, natural fiber/filler reinforced polymer (NFRP) composites are gaining significant importance in different sectors such as automotive, aircraft industries, furniture's, packaging and construction due to their advantages over synthetic fiber [1]. Furthermore, NFRP composites are eco-friendly, recyclable, biodegradable and abundantly available. Examples of natural fiber composites that are used in various applications include jute, ramie, cotton, banana, sisal, wood, flax, bamboo, hemp, areca etc. [1].

Among the different natural fillers, the most commonly used natural fillers are pineapple leaf based fillers (PLF). PLF is widely grown in the entire region of India such as Assam, Tripura, Meghalaya, Manipur, West Bengal, Gujarat, Karnataka, and Kerala etc [2]. Besides, many fruit bearing plants, the pineapple plant bears fruit only once in its lifetime, beyond which the plants are left to die and decay as an agro waste. Thus, instead of letting the plant to decay as an agro waste they can be used for some potential applications by extraction of fibers/fillers from the leaves. The extracted leaves can be further utilized in many applications such as fabric, automobile, furniture and sports industries as an alternative to synthetic fibers/fillers [3]. Furthermore, a synthetic fiber such as glass is available in high density, non-degradable, costly and cause environmental issues. To overcome these difficulties, synthetic fibers can be replaced with PLF; this offers lower weight, less costly, biodegradable and environmentally friendly. Several studies have been carried out on determination of physical and mechanical properties of PLF based polymer composites and compared the results with glass fibers. Furthermore, with upcoming demand of pineapple fillers based polymer (PFRP) composites, machining, especially cutting of these materials with different shape with high superior finish, and higher productivity at minimum machining costs and maximum machining effectiveness, have become an important issue to investigate the machinability behavior of these materials. In addition, these composites are subjected to extensive machining operations before actual use.

Beside, its advantages and applications; due to the anisotropic and inhomogeneous properties, the machining of PFRP compsoites by conventional process (such as, drilling, milling, sawing, and grinding etc) is very difficult and a costly endeavor [4] and also produces environmental burdens during machining. Hence, in order to overcome these limitations non-traditional machining processes are preferred [4]. Since, the PFRP compsoites are of non-conductive nature; the electrical discharge machining (EDM), wire-electrical discharge machining (WEDM), and electrochemical machining (ECM) processes cannot be used. On the other hand, the laser cutting can be used but this process suffers from the problem of a large heat-affected zone, which results in melting of PFRP composites due to lesser thermal conductivity. Furthermore, ultrasonic machining (USM) can be used for machining of PFRP composites, but limited to metal matrix composites and ceramic matrix composites. This process also possesses work piece and tool size limitations [5] and it is a slow process as well [6]. In spite of these problems, non-traditional machining processes are considered as hazardous process because in which large amount of harmful elements in the form of solid, liquid, and gaseous wastes are discharged; resulting in serious occupational health and environmental issues[7]. To overcome these limitations, abrasive water jet machining (AWJM) is used for machining of PFRP composites. AWJM process is capable of machining ductile and electrically non-conductive materials with better material removal rate [8, 9]. Another added advantage of AWJM process is that it doesn't require any extra coolant and lubricants as water by itself acts as a tool as well as coolant and lubricant which makes it an eco-friendly and green manufacturing process. However, there is a scarcity of work on machining of PFRP composites using AWJM process. This study aims to explore capability of AWJM process to machine PFRP composites with high productivity and surface quality. A detailed investigation on the effect of AWJM parameters such as stand-off distance, work pressure, nozzle speed, abrasive grain size on machinability indicators namely material removal rate, and average surface roughness has been done. Optimum values of process parameters have also been obtained for the best values of the aforementioned machinability indicators. The subsequent sections details the various stages of this experimental study.

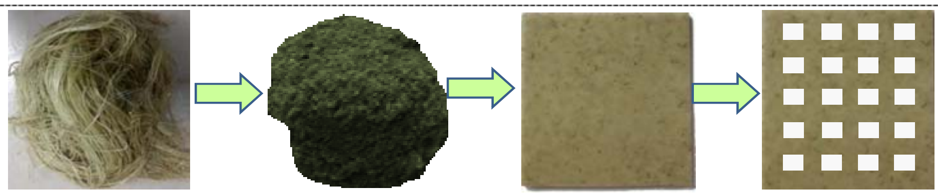
2. Material and Method

2.1. Workpiece preparation

The present study utilizes pineapple leaf filler (PLF) as reinforcement material with density of 1520 kg/m^3. Initially the pineapple leaves are collected and soaked in water for a span of approximately 2 weeks. After the stipulated time period, due to bacterial fermentation the gummy portion of leaf surrounding the fiber becomes soft and swollen [10, 11]. Now with the aid of blunted object the gummy portion is manually scraped out leaving behind the fiber. The fiber is then thoroughly rinsed in distilled water and dried under the sun or oven. The fiber is then converted into powder form for mixing with matrix. The chief constituents of PLF are cellulose, lignin and ash [12, 13]. The matrix used is epoxy (Araldite LY 556) with density of 1160 kg/m^3 and a corresponding hardener (HY951) with density of 950 kg/m^3, which are mixed in the ratio of 10:8 by weight [13]. To this mixture, 3% of PLF is added and mechanically stirred until a homogenous mixture is obtained [13]. Thereafter the mixture is poured in to the mold kept inside the vacuum glass chamber and allowed to cure for 24 to 48 hrs at room temperature. The obtained specimen of size 180 mm x 150 mm x 5 mm is then taken for further machining. The pineapple leaf fiber along with the prepared composite and the machined specimen are shown in Figure 1.

2.2 Experimental procedure

In the present work four independent process variables, which significantly affect the performance of the process such as SoD, WP, NS, and AGS are selected with three levels each. Even though the full factorial array covers all the possible combination of factors (LP= 34 =81), it is a costly and time consuming process, especially when the number of process variables are more [14]. Hence, in the present study, Taguchi orthogonal array (OA) is used to reduce the number of experiments without considerably affecting the accuracy of the results. The minimum number of experimental runs calculated using Taguchi orthogonal array is found to be nine (9) [1+4 (3-1) = 9] for four parameters with three levels. The values of the process parameters and their corresponding levels are shown in Table 1. Machining of PLFP composite has been carried out using CNC abrasive water jet cutting machine (Figure 2) manufactured by DARDI International Corporation, China. Throughout the experiment the discharge rate and orifice diameter are fixed at 2.31 l/min and 0.25 mm respectively with maximum possible water pressure being limited to 3800 bar. Square holes of size 20 mm X 20 mm have been cut during the experiment from the PFRP composite of dimension 180 mm $\times$ 140 mm $\times$ 6 mm.



a) (b) (c) (d)

Figure 1. (a) Extracted pineapple leaf fiber (b) pineapple leaf filler (c) prepared composite (d) machined specimen.

Table 1. Details of input process parameters

Input parameters	Unit	Symbol	Level 1	Level 2	Level 3
Stand of Distance	mm	SoD	1	2	3
Work Pressure	MPa	WP	100	125	150
Nozzle Speed	mm/min	NS	100	200	300
Abrasive Grain Size	mesh	AGS	70	80	90

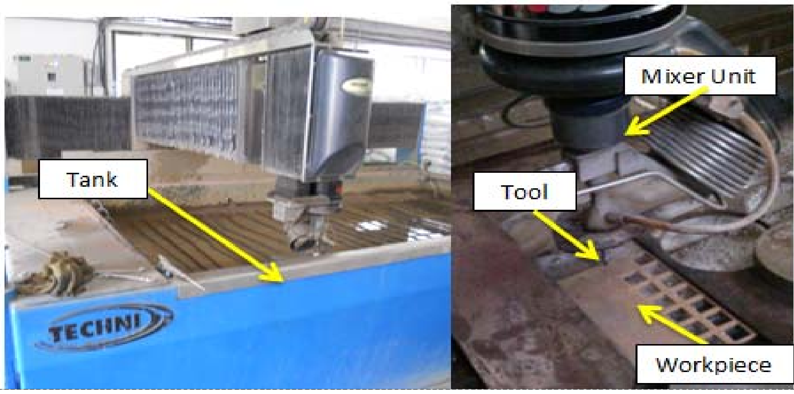


Figure 2. Experimental setup.

The experiment repeated thrice for each set of parameter conditions as per the orthogonal array and the average values were taken for calculation of material removal rate (MRR), and surface roughness (SR) (see Table 2) in order to minimize experimental errors and obtain accurate results [14]. The surface roughness is measured using surface profilometer (Make: Tokyo Seimitsu Co. Ltd. Model: Hanhysurf E-35B) and the MRR is calculated by measuring the weight of the composite before and after machining and the time taken for machining [15] using the Eq. (1).

$$MRR = \frac{W_B - W_A}{T} \tag{1}$$

where, W_A is the weight of the composite after machining and W_B is the weight of the composite before machining, while T is the time taken for machining a 20 X 20 mm hole.

Table 2. Experimental results corresponding to nine combinations of AWJM parameters

Ex. No.	Input parameters				Output parameters	
	SoD (mm)	WP (MPa)	NS (mm/min)	AGS (mesh)	MRR (g/s)	SR (μm)
1	1	100	100	70	03.251	0.150
2	1	125	200	80	12.652	0.143
3	1	150	300	90	28.927	0.172
4	2	100	200	90	24.956	0.130
5	2	125	300	70	47.853	0.135
6	2	150	100	80	18.6251	0.185
7	3	100	300	80	66.771	0.160
8	3	125	100	90	24.784	0.102
9	3	150	200	70	55.551	0.178

3. Results and discussion

The effect of input parameters such as SoD, WP, NS and AGS on MRR is shown in Figure 3. From the graph, it is observed that there is an increasing trend for MRR with increase in SoD and NS. The reason for this can be attributed to the fact that as SoD increases the area over which the water impacts increases and eventually more material gets removed, whereas the nozzle speed increases the kinetic energy of the abrasive particles present inside the nozzle increases and hence more energy is imparted to the

workpiece for material removal mechanism [16]. Besides, SoD and NS, other factors did not influence MRR much (see Figure 3). In the case of WP, MRR decreases as WP increases from 100 MPa to 125 MPa and at 150 MPa, the MRR increases considerably. As the WP at higher level increases, it increases the kinetic energy of the abrasive particles inside the nozzle, which results in higher MRR as observed in Figure. 3. Moreover, a marginal decrement of MRR is observed (see Figure. 3) as AGS increases from 70 mesh to 90 mesh. This is mainly because, as the mesh size increases particle size of abrasives decreases and small abrasive grain cover less area when bombarded on the composite surface resulting in reduced MRR. Thus, it is observed that, parameter SoD and NS are found to be most significant while parameter AGS is least significant on the AWJM responses during PFRP composites machining. Moreover, parameter WP is found to be moderate influence on the responses. From the analysis, the optimal combinations of input parameters for higher MRR are
SoD (3 mm, level 3), WP (150 MPa, level 3), NS (300 mm/min, level 3) and AGS (70 mesh, level 3).

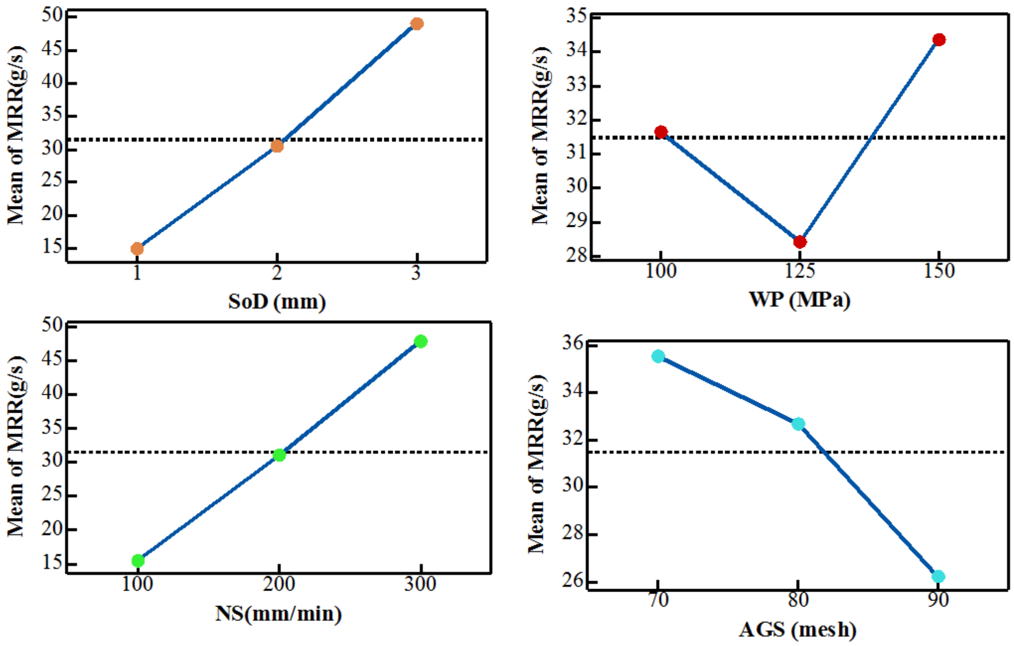


Figure 3. Effect of process parameters on MRR.

On studying the effect of input parameters on surface roughness (Figure 4), it is observed that surface roughness decreases with increase in SoD. It is because as SoD increases, the jet diameter increases due to air drag, which ultimately reduces the kinetic energy density of the jet at the point of impact with the workpiece [16]. Hence, low SoD gives high kinetic energy and better surface finish. With increase in NS, surface roughness increases because of the fact that as NS increases, the kinetic energy of abrasive particles increases and more material is removed from the workpiece, which causes an increase in surface roughness [12]. In case of WP, surface roughness first decreases (0.146 µm to 0.126 µm) with increase of WP and then increases (0.126 µm to 0.178 µm). This is because at low WP, the penetration is less and hence less SR due to less material removal and as WP increases the SR increases as observed at 150 MPa due to higher penetration and hence higher SR. On the other hand, the effect of AGS on the SR found to be moderate i.e. increase of SR from (0.155 µm) at 70 mesh to (0.162 µm) at 80 mesh then it drastically decreased to 0.134 µm at 90 mesh. This is because, as the AGS (mesh size) is increased (70 to 90 mesh) mean grain size of the abrasives gets reduced to smaller size, resulting in lesser material removal and smoother surface as observed in Figure.4. Therefore, it is desirable to have higher values of mesh size for abrasives to get the smoother SR in the case of PFRP composite. Thus, parameter WP and NS found to be most significant while parameter SoD is least significant on the AWJM responses during PFRP composites machining. From the analysis, the optimal combination of input parameters for lower SR are SoD (3 mm, level 3), WP (125 MPa, level 2), NS (100 mm/min, level 1) and AGS (90 mesh, level 3).

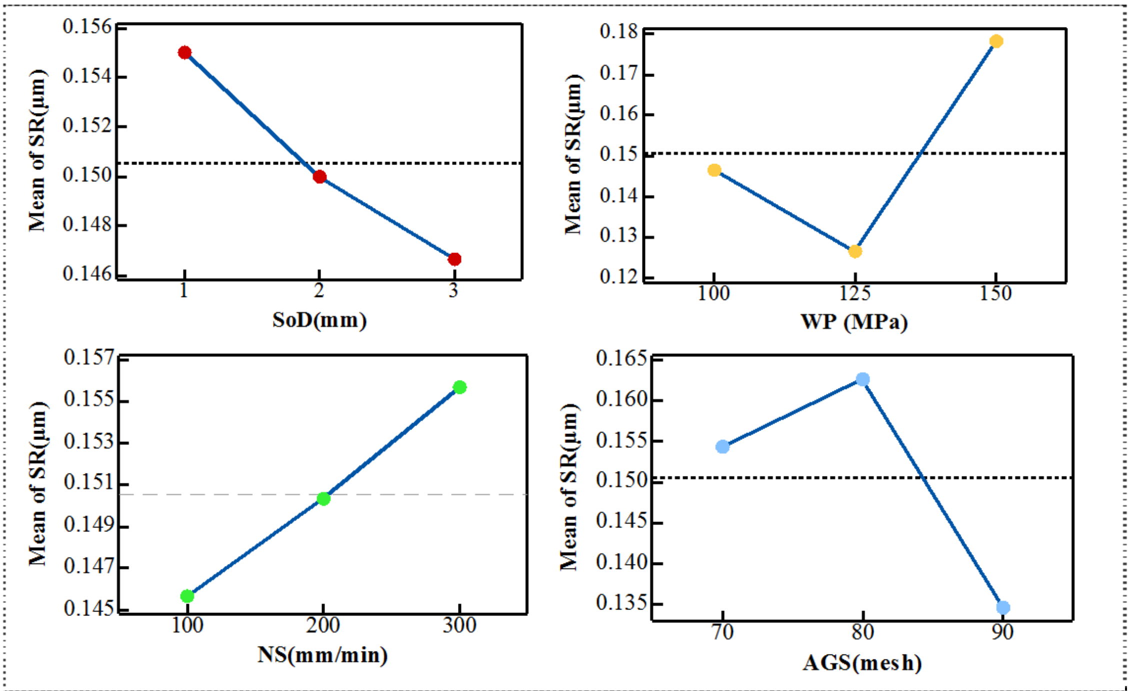


Figure 4. Effect of process parameters on SR

At last, validation of the optimum results obtained from parametric analysis is carried out via confirmatory tests and results are depicted in Table 3. From the results, it is observed that, results for MRR and SR are found to be comparable and acceptable with experimental results.

Table 3. Results of confirmation tests.

Response Parameters	Exp. Results	Optimum Parameters				Confirmatory Test Result
		SoD (mm)	WP (MPa)	NS (mm/min)	AGS (mesh)	
MRR	66.77	3	150	300	70	71.07
SR	0.143	3	125	100	90	0.131

4. Conclusion

The present paper reports an experimental investigation carried out to machine PFRP composites by AWJM process. Effects of process parameters on MRR and SR have been studied. Nozzle speed is the most significant in case of surface roughness, while stand-off-distance and nozzle speed are more significant in the case of material removal rate. The optimum machinability indicators obtained are MRR- 71 g/s, and average roughness- 0.13 µm. The optimal setting for optimum MRR is found to be- SoD (3 mm, level 3), NS (300 mm/min, level 3), WP (150 MPa, level 3) and AGS (70 mesh, level 1); while optimum settings for SR are SoD (3 mm, level 3), WP (125 MPa, level 2), NS (100 mm/min, level 1) and AGS (90 mesh, level 3). Based upon the outcomes of the present study, it can be concluded that

AWJM process is a vital substitute of conventional processes for machining PFRP composites with high productivity, surface quality and sustainability.

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